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**MEASUREMENTS OF ICE PARTICLES IN TROPICAL CIRRUS ANVILS:
IMPORTANCE IN RADIATION BALANCE**

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1. INTRODUCTION

Cirrus is important in the radiation balance of the global atmosphere, both at solar and thermal IR wavelength. In particular cirrus produced by deep convection over the oceans in the tropics may be critical in controlling processes whereby energy from warm tropical oceans is injected to different levels in the tropical atmosphere to subsequently influence not only tropical but mid latitude climate (Ramanathan and Collins, 1991). Details of the cloud composition may differentiate between a net cooling or warming at these levels (Liou, 1986). The cloud composition may change depending on the input of nuclei from volcanic or other sources (Sassen, 1992). Observations of cirrus during the FIRE II Project over Coffeyville, Kansas (Arnott, et al, 1994i) and by satellite demonstrate that cirrus, on occasion, is composed not only of larger particles with significant fall velocity (few hundred μm , $\frac{1}{2} \text{ m s}^{-1}$) but much more numerous small particles, size 10 - 20 μm , with small fall velocity (cm s^{-1}), which may sometimes dominate the radiation field. This is consistent with emissivity measurements (King et al, 1993). In the thermal IR, ice absorption is strong, so that ice particles only 10 μm thick are opaque, at some wavelengths; on the other hand at other wavelengths and in the visible, ice is only moderately to weakly absorbing. It follows

that for strongly absorbing wavelengths the average projected area of the ice particles is the important parameter; in weakly absorbing regions it is the volume (mass) of ice which is important. The shape of particles and also their internal structure may also have significant effect on their radiative properties (Liou, 1986, Arnott et al. 1994ii).

In order to access the role of cirrus in the radiation budget it is necessary to measure the distribution of ice particles sizes, shapes and concentrations in the regions of interest. A casual observation of any cirrus cloud shows that there is variability down to a scale of at least a few 10^6 m ; this is confirmed by radar and lidar remote sensing. Thus aircraft measurements designed to give insight into the spatial distribution of radiation properties of ice crystals must be capable of examination of concentration, size and shape over a distance ideally of 100 m or less and to detect particles down to a size below which radiative effects are no longer significant.

2. INSTRUMENTATION

Measurements were made during the TOGA COARE Project, using the NASA DC-8 aircraft, in flights over the W. Pacific Jan./Feb. 1993. In view of the importance of tropical cirrus in

the radiation balance, these measurements were specifically designed to cover the range of particles important in the radiation balance with a sampling rate of each instrument of some liters per second. Larger particles ($> 100 \mu\text{m}$), were detected by the 2 DC PMS optical probe and smaller particles $\geq 5 \mu\text{m}$ by a formvar replicator which collected particles through a 3 mm slit in a plastic solution to leave permanent casts. In parallel, measurements, were made of total nuclei (CN by a TS1 3010 instrument), which detects particles down to $< 0.01 \mu\text{m}$; details of these measurements are being published elsewhere (Hudson et al 1995). Data is analyzed from a few seconds to 200 s of flight path representing $\frac{1}{2}$ km and 20 km path lengths. This enables measurement of the lower concentration of larger particles to give more relevant statistical data.

3. OBSERVATIONS

Deep cumulonimbus convective clouds grow, subject to local dynamical forcing, over the west Pacific warm pool to altitudes $> 50,000$ ft and top temperatures $< -70^\circ\text{C}$. These clouds give ice anvil as they extend through the -40°C level which is spread away from the main vertical motion in winds prevailing aloft. Instrumentation was carried by the NASA-DC-8 which flew typically up to 42,000 ft with local air temperatures down to -55°C . Penetrations were made of anvils, not necessarily near the tops, which on occasion extended well above the highest flight level. Some penetrations were also made at lower levels. The data presented here were selected from flights where good quality replica and PMS data were collected. Initial analysis consists of size, habit, and concentration from PM 2DC images and from replica. Caveats in the data are that "null" images in the PMS (one pixel) need to be distinguished from noise, giving an effective lower limit for detection of two pixels, and of habit estimation of some 10 pixels in diameter. The replicator was mounted in a standard PMS pod and transported film at 2 cm s^{-1} , sampled through a 3 mm slot. Thus each 16 mm film frame collected crystals from a 200 m path. In principle, a "point" analysis of 3 mm of film gives a minimum resolution of 50 m. Sampling of particles; below a few μm size falls off because of reduced collection efficiency; particle "noise" in the solution and film

also possesses problems of interpretation, for such small particles. Particles greater than a few $100 \mu\text{m}$ shatter on collection (which can be reconstructed); more serious is that they may shatter on entry into the slit itself. These fragmented particles can largely be excluded from analysis by a consideration of the concoidal fracture consistent with high speed impact of a brittle solid - as occurs in shatter of a glass window. In parallel with the ice measurements, data was obtained with a FSSP-300 X with 15 channels centered between 0.4 and $20 \mu\text{m}$. The data from this type of instrument in ice is open to interpretation. Gardiner and Hallett (1985) showed that counting of supercooled cloud droplets in the presence of some ice particles was enhanced; the shape and internal structure of small ice particles has potential for influencing counts. Overall estimate is a potential for $\times 10$ enhancement from replica from the conditions for shatter, and a comparable factor for FSSP total counts. A comparison of small particles by both techniques is made here, which give comparable results and some confidence in the measured concentrations.

4. RESULTS

Measurements of replica, PMS - 2DC data, and FSSP data (Flight 12 only) are shown in composite plots at specific times and temperature. Data represent integration over about $\frac{1}{2}$ minute, representing about 5 km of flight path. Fig. 1 shows data from an anvil at a temperature of -55°C . Replica and 2 D-C are in sufficient agreement on the region of overlap around $100 \mu\text{m}$. It is noted that the concentration rises with decreasing size to the effective limit of replica analyzed - in this case about $10 \mu\text{m}$. (The smaller crystals were examined using microscopy; the large ones by projection). The plot suggests a greater number than a straight line extrapolation log concentration plot of the larger size particles suggest. Composite data including PMS counts are shown in Fig. 2, which suggests even larger numbers at smaller size (nominally to $0.3 \mu\text{m}$). The number concentration near $10 \mu\text{m}$ are consistent between FSSP and replica; there is also consistency in the overlap region between replica and 2D-C probe near $100 \mu\text{m}$.

Figure 1a, b: Anvil from old convection; flight 15. Temperature -55°C. Time: 22 34 59 - 22 35 15z. 17 Feb. 1993. LAT: 40° 20; LONG: 155° 00 E. Replica and PMS - 2D data, effective overlap 75 - 200 μm . Replica and PMS data are consistent in overlap region. Squares are PMS 2D-C; others replica for various analyses.

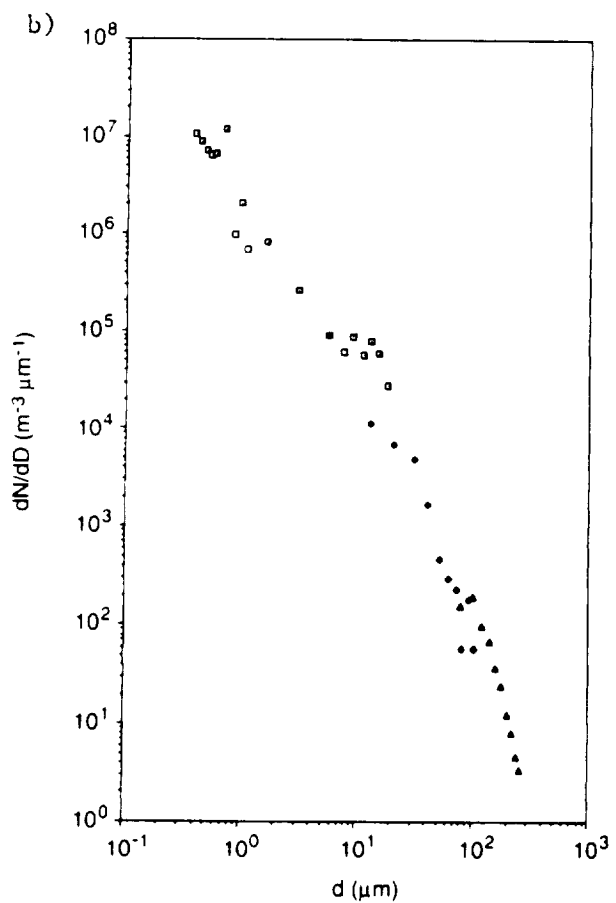
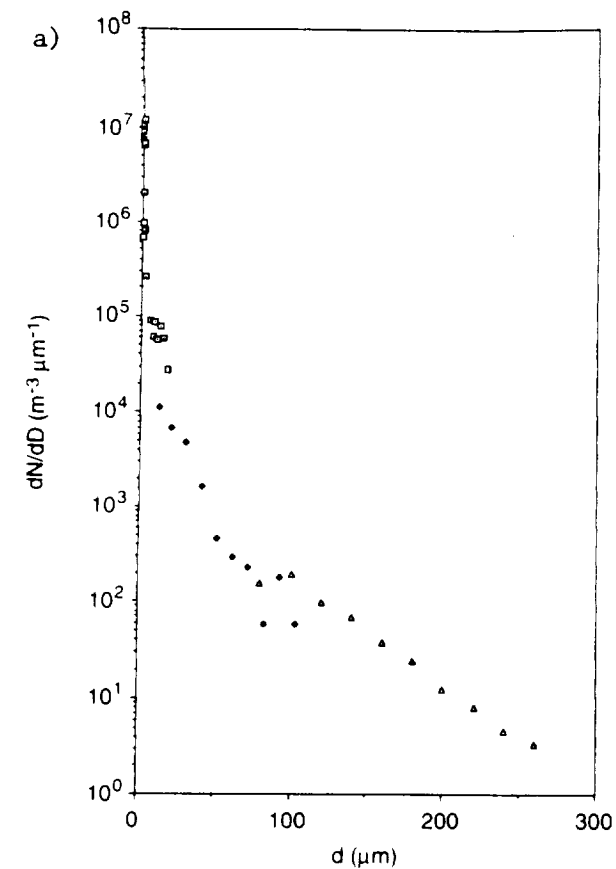


Figure 2a, b: Anvil outflow from Hurricane Oliver; 17 11 52 - 17 12 34z. Flight 12, 6 Feb. 1993. Temperature -46°C. Replica - 2D-C data overlap 75 - 150 μm ; FSSP - replica overlap 10 - 20 μm . LAT: 11° 20 S. LONG: 155° 15 E. Squares are FSSP; others are replica.

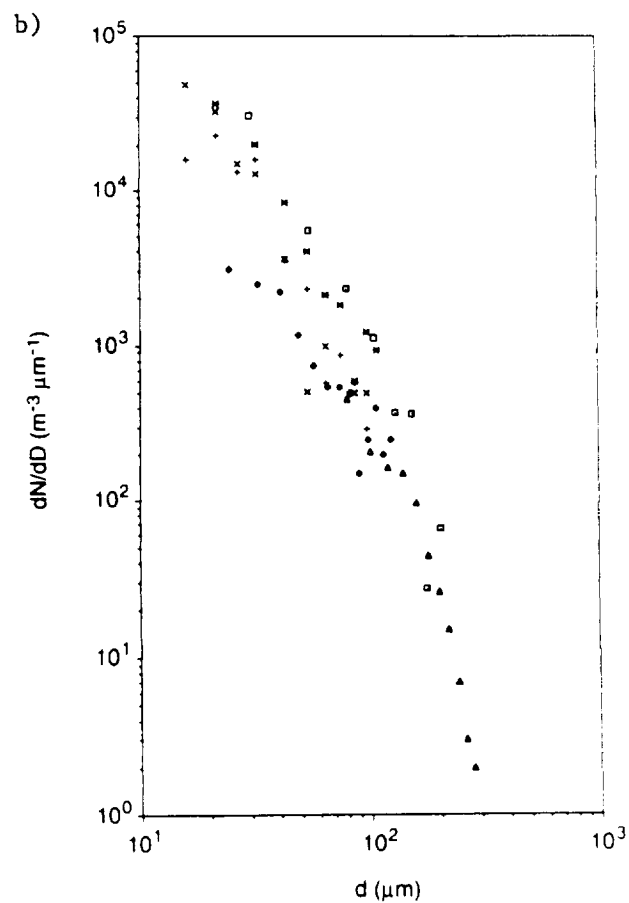
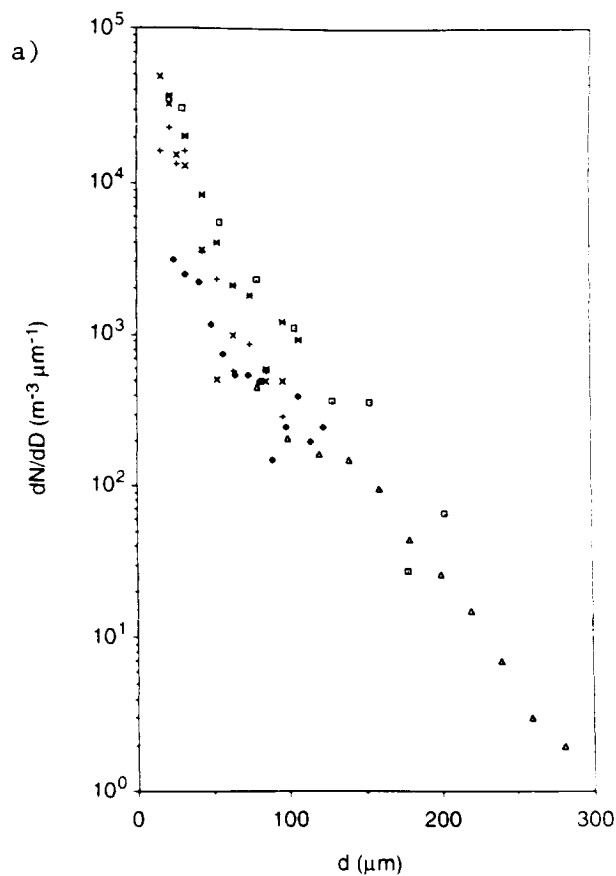


Figure 3 shows a composite data set of replica and 2D-C where consistency in counts occurs near $100\ \mu\text{m}$, but replica shows smaller numbers of particles larger than this size by a factor of about 5. Such discrepancy can be attributed to a more fragile structure of the large crystals, which break prior to replication observation of a large number of rejected shattered fragments are consistent with this possibility.

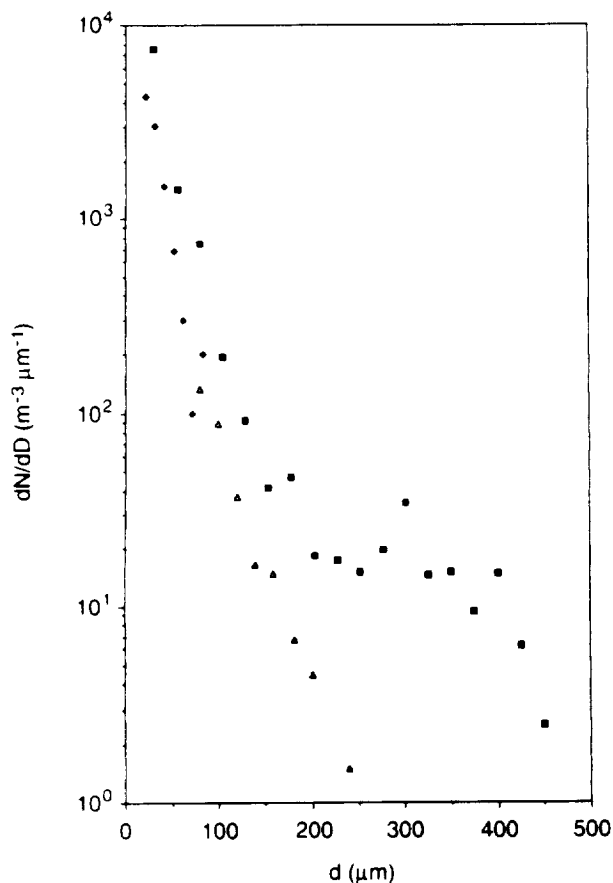


Figure 3: Anvil from old convection; descending cirrus plume. Flight 18; 24 Feb. 93. Temperature - 28°C , 22 37 21 - 22 37 49z. Approx: LAT 151° LONG: 2°S . Replica and PMS 2DC effective overlap 75 - $200\ \mu\text{m}$. Replica gives fewer particles than PMS for size $> 150\ \mu\text{m}$. Squares are PMS 2DC.

Figure 4a, b: shows a plot of area and volume (equivalent circle diameter) related to sizes suggesting a maximum contribution of particles 15 - $20\ \mu\text{m}$ diameter, with a replica fall-off for large particles $> 100\ \mu\text{m}$.

Neither PMS or replica showed any significant evidence for crystal aggregation at any level.

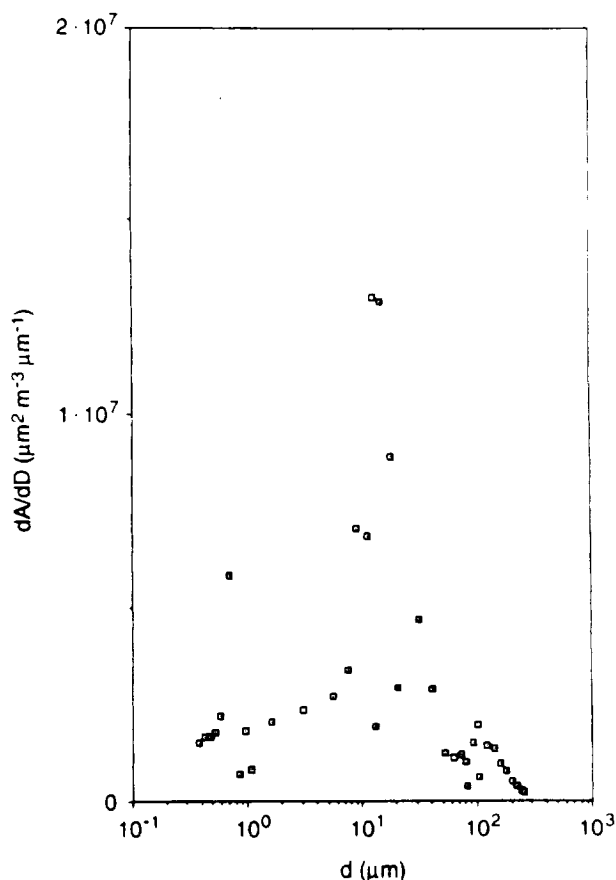


Figure 4a: Derived area of particles from in Fig. 2 from (flt 12) assuming an equivalent circle diameter. This data suggests a maximum area contribution for particles near 15 - $20\ \mu\text{m}$ size.

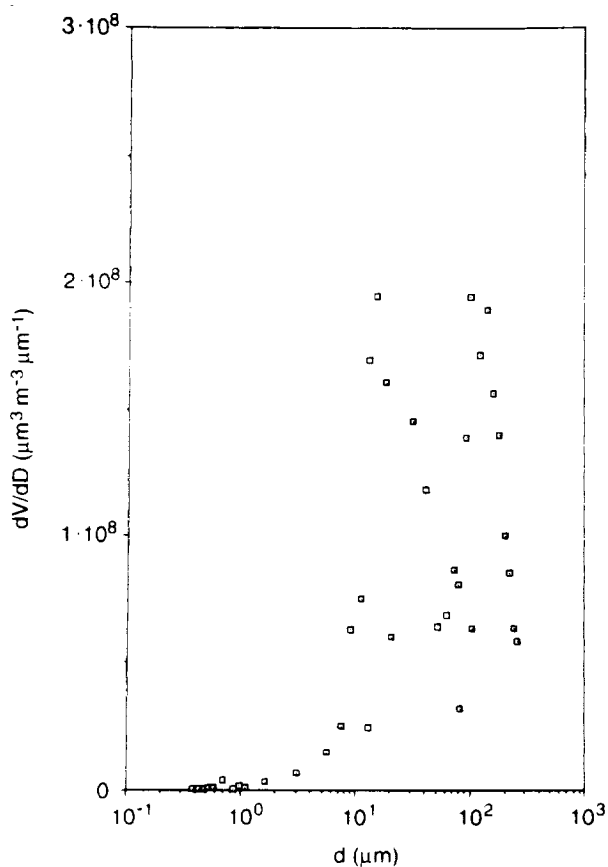


Figure 4b. Derived volume distribution showing a wide maximum contribution of particles 20 to 100 μm .

5. DISCUSSION

The most important result from these observations is the presence of large numbers of particles of size below 50 μm which contribute significantly to the effective surface area and opacity of the ice layer. It is important that the presence of the particles is shown in data obtained from two quite independent techniques - replicator and FSSP. It is to be noted that the numbers are well in excess ($\times 100$) of those found by the ER2 at higher levels in the STEP Project (Knollenberg et al 1993) using a different FSSP with a much lower response to these sizes of particles. The presence of such particles is apparent in all 3 cases chosen for analysis, at temperatures -28, -45 and -55°C. In the former case, the penetration was through a descending region of ice from a higher layer aloft; this shows that such small particles are preserved in such weak vertical motions. It is of interest that CN measurements made during these flights, showed, on occasion, counts as high as 5,000 cm^{-3} (compared with "normal" background of a few hundred cm^{-3}). Volatility analysis in a controlled furnace showed that these particles evaporated near

120°C, strongly suggesting that their composition was sulfuric acid. Such numbers are consistent with observations of Clarke (1993). The ice particle concentration at the smallest size examined is a few cm^{-3} , indicating that only a fraction of the aerosol is activated to become ice particles. This implies that there could be present in the cirrus, in addition to the small ice particles, even larger number of inactivated sulfuric acid haze particles. Should the region of air containing such particles be subsequently lifted, further activation and freezing could ensue as particles dilute and freeze homogeneously. The origin of the initially large ice concentration is of interest. Qualitatively, a significant parameter is the temperature at which condensation begins on any aerosol present. Cloud bases of deep convection are at temperatures well above +20°C, so that the initial droplet spectrum is formed by the usual competitive process at these levels, controlled by the surface CCN spectrum and cloud base updraft. Much happens before these particles reach higher colder levels where ice nucleation begins - warm rain removes much water substance, nuclei are scavenged by various processes and incorporated by mixing from higher levels as the cloud builds upwards. The ultimate ice concentration, as homogeneous nucleation takes over after passing -40°C, can be envisioned to result from an identical competitive process whereby nuclei are diluted and frozen homogeneously, depending again on the tail of the CCN spectrum and vertical velocity. A knowledge of the complete cloud properties (CN, CCN, vertical velocity), it is vital in understanding the ice origin. The origin of the nuclei ALOFT can be speculated to be possibly from the surface - advected in strong convection, and possibly from moderate volcanic activity which is always going on in the W. Pacific. The relative role of volcanic and ocean production is an area for potentially fruitful speculation.

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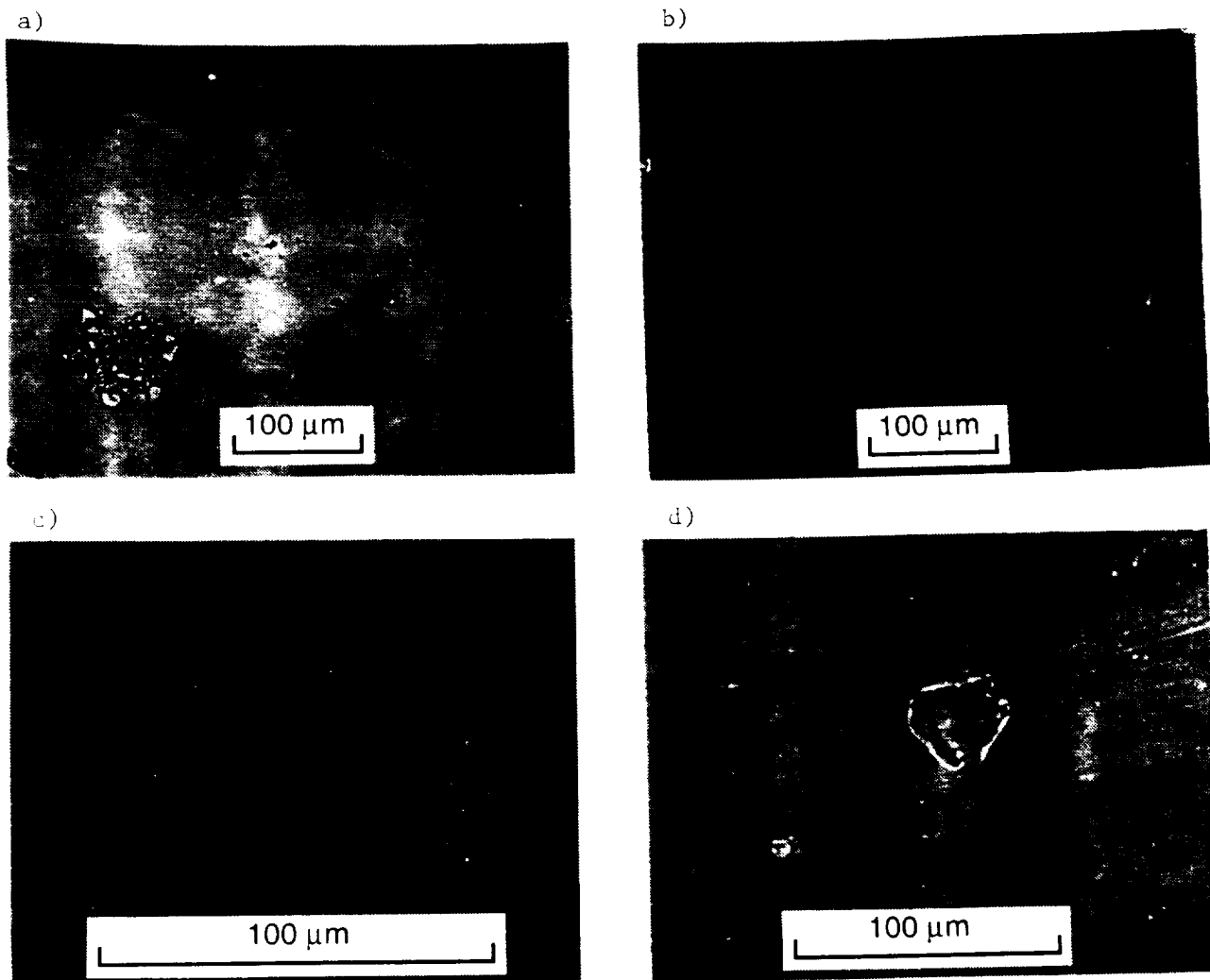


Figure 5. Examples of formvar replica: a) partly fragmented polycrystal, showing crystals with hexagonal periphery. b) hexagonal plate, with shatter fragments from other crystals (these would not be counted as individual crystals). c) columns, partly shattered on collection (flt 12). d) crystal showing trigonal symmetry (flt. 17).

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